# Environmental Assessment of Road Dust at Bus Stops in Villavicencio, Colombia

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## Abstract

The accumulation of potentially toxic elements (PTEs) in road dust poses a significant risk to the environment and public health, especially in urban areas with high traffic density. However, few studies have assessed these risks in environments such as university bus stops, particularly in Colombia. The objective of this study was to assess the pollution levels and potential risks associated with lead (Pb), cadmium (Cd), copper (Cu), and zinc (Zn) in road dust collected at bus stops at Universidad de los Llanos, in Villavicencio, Colombia. Dust samples were collected from eight bus stops using a brush and tray over 1 m² areas, with five subsamples per site along 100-meter stretches. The samples were stored in polyethylene bags and homogenized using a 2.0-mm sieve. Concentrations of heavy metals (Pb, Cu, Zn, Cd) were determined by microwave-assisted acid digestion followed by Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES) analysis. The mineralogical composition was analyzed through X-ray diffraction (XRD) using Cu Kα radiation (λ = 1.54060 Å) in a range from 2° to 70°. The levels of all elements exceeded the background values for the area. Pb concentrations ranged from 15.0 to 44.6 mg $kg^{-1}$, Cd levels ranged from 0.6 to 1.2 mg $kg^{-1}$, Cu levels ranged from 17.6 to 115.6 mg $kg^{-1}$, and Zn levels ranged from 69.8 to 519.6 mg $kg^{-1}$. The geoaccumulation index and the integrated pollution index indicated significant contamination with copper and zinc being the most abundant elements. The ecological risk assessment revealed cadmium as the greatest potential threat. The results underscore the need to implement stricter environmental controls and urban development strategies to reduce PTEs exposure in areas near public transportation. The findings of this study provide key information for policymaking aimed at improving air quality and soil management in urban settings.

***Keywords:*** Bus stops, Heavy metal, Pollution Indexes, Urban environmental quality, Road dust.

## Evaluación ambiental del polvo de carretera en paraderos de bus de Villavicencio, Colombia.

## Resumen

La acumulación de elementos potencialmente tóxicos (EPT) en el polvo de carretera representa un riesgo significativo para el medio ambiente y la salud pública, especialmente en zonas urbanas con alta densidad vehicular. Sin embargo, pocos estudios han evaluado estos riesgos en entornos como los paraderos de autobús universitarios, particularmente en Colombia. Este estudio tuvo como objetivo evaluar los niveles de contaminación y los riesgos potenciales t asociados con Pb, Cd, Cu y Zn en el polvo vial recolectado en paraderos de autobús de la Universidad de los Llanos, en Villavicencio, Colombia. Se recolectaron muestras de polvo en ocho paraderos utilizando cepillo y bandeja sobre áreas de 1 m², con cinco submuestras por sitio a lo largo de un tramo de 100 metros. Las muestras se almacenaron en bolsas de polietileno y se homogeneizaron con un tamiz de 2,0 mm. Las concentraciones de metales pesados (Pb, Cu, Zn, Cd) se determinaron mediante digestión ácida asistida por microondas, seguida de análisis ICP-OES. La composición mineralógica se analizó mediante difracción de rayos X (DRX) con radiación Cu Kα (λ = 1,54060 Å), en un rango de 2° a 70°. Los niveles de todos los elementos superaron los valores de fondo para la zona. Las concentraciones de Pb oscilaron entre 15,0 y 44,6 mg $kg^{-1}$, Cd entre 0,6 y 1,2 mg $kg^{-1}$, Cu entre 17,6 y 115,6 mg $kg^{-1}$, y Zn entre 69,8 y 519,6 mg $kg^{-1}$. El índice de geo-acumulación y el índice integrado de contaminación indicaron una contaminación significativa, siendo el cobre y el zinc los elementos más abundantes. La evaluación del riesgo ecológico reveló que el cadmio representa la mayor amenaza potencial. Los resultados subrayan la necesidad de implementar controles ambientales más estrictos y estrategias de desarrollo urbano para reducir la exposición a EPT en zonas cercanas al transporte público. Estos hallazgos ofrecen información clave para la formulación de políticas orientadas a mejorar la calidad del aire y la gestión del suelo en contextos urbanos.

***Palabras clave:*** Calidad ambiental urbana, Índices de contaminación Paraderos de autobús, Polvo de carretera, Metales pesados

## Introduction

The development of infrastructure to support a constantly expanding population generates particulate matter that accumulates in soil, posing significant risks to human health and the environment (Meza-Figueroa et al., 2007). Some of the most common sources of anthropogenic particulate matter are asphalt, road paint, vehicle emissions (such as tire and brake dust), industrial by-products, and atmospheric deposition from different human activities (Adachi and Tainosho, 2005). Among the pollutants present in this particulate matter, Potentially Toxic Elements (PTEs) stand out due to their increasing threat to human health and the environment, particularly in urban areas with high traffic density. These pollutants tend to accumulate on heavily trafficked surfaces, such as bus stops, creating persistent exposure risks for individuals frequenting these areas. Consequently, PTEs have become pollutants of widespread concern at road dust sites, particularly at bus stops. Thus, many research studies, especially in recent times, have found different amounts of PTEs in road and city dust (Nezat et al., 2017; Trujillo-González et al., 2019; Jeong and Ra, 2022; Abu Khatita, 2023), with copper (Cu), lead (Pb) and zinc (Zn) being the most common.

As a matter of fact, extensive studies have researched the various causes and variables that cause PTEs to occur in urban road dust. Major sources include traffic-related emissions, such as vehicle exhaust particulates, tire and brake degradation, and road surface erosion, as well as industrial emissions from power plants, metallurgical sectors, and chemical manufacturing plants. Additional sources include household emissions, deterioration of building and pavement materials, and atmospheric deposition (Ordonez et al., 2003; Duzgoren-Aydin et al., 2006; Amato et al., 2009; Faiz et al., 2009; Yang et al., 2021). Furthermore, research has emphasized the impact of atmospheric deposition, land use, climatic factors (such as wind, precipitation, and temperature), and the physicochemical characteristics of soil and dust on PTEs contamination levels (Li et al., 2017; Zupančič, 2017; Feng et al., 2019; Zhou and Wang, 2019; Pecina et al., 2021). Therefore, in cases such as those mentioned, as in other polluting processes, various indices and approaches have been used to assess the degree of pollution or enrichment of PTEs, including the single-factor index, geo-accumulation index (Müller, 1982; Li, 2019), and the Pollution Load Index (PLI) (Cheng et al., 2019).

Among the contaminants commonly found in road dust, the most hazardous PTEs are Cu, cadmium (Cd), Zn, and Pb. These elements are particularly concerning due to their ability to transfer from dust or soil directly into aquatic and terrestrial food chains, posing significant risks to both wildlife and human health (Adimalla et al., 2020). Research on heavy metal contamination in road dust remains limited in Colombia, particularly in urban areas such as Villavicencio, where the increasing number of vehicles and rapid infrastructure development exacerbate this problem. In fact, regarding this issue, Trujillo-González et al., 2019, identified substantial lead contamination in road dust in Villavicencio, which highlights the severity of the problem. In a later study, Trujillo-González et al. (2025) analyzed heavy metal levels in two smaller municipalities, Puerto López and Puerto Gaitán. This study added to the evidence that PTEs pose long-term environmental risks in both urban and peri-urban areas.

As far as is known, the existing literature has not adequately examined specific scenarios related to health risk assessments of urban pollution in bus stop areas. Urban soil contamination with PTEs in Colombia has become a pressing problem, primarily due to the rapid industrialization and urbanization over the last two decades, as demonstrated by the circumstances in Villavicencio. However, within the Colombian academic community, there is a notable shortage of research focused on exposure to and the hazards associated with pollution. This highlights the need for research that quantifies and systematically assesses these risks in a comprehensive and holistic manner.

In this context, the main objectives of this study were: (a) to determine the concentration of potentially toxic elements (PTEs) present in urban dust collected at bus stops on a university campus in Villavicencio, Colombia; (b) to compare these concentrations and contamination levels with those reported in other national and international research; and (c) to assess the potential Ecological Risk Factor (Er). These initiatives aim to establish a scientific basis for the assessment, governance, and effective management of risks related to PTEs contamination in urban environments.

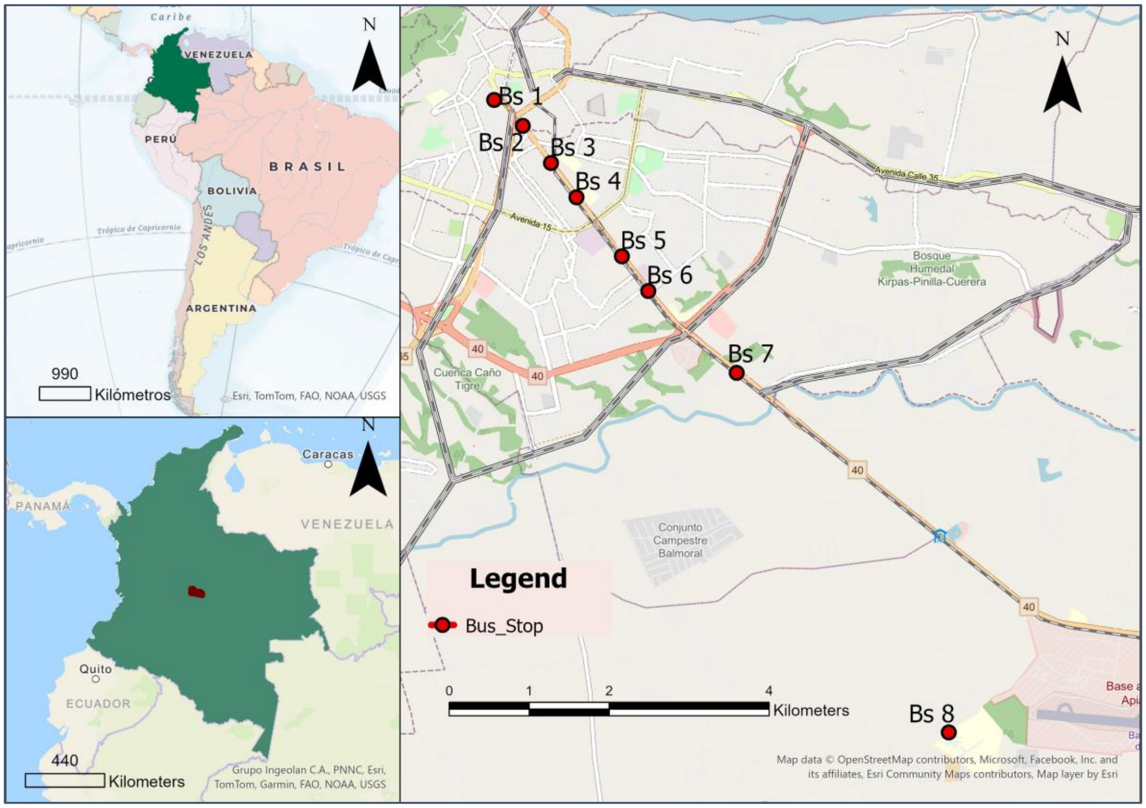
## Materials and methods

### *2.1. Study area and Road Dust Sampling*

This study was conducted at bus stops along a route to a university in Villavicencio, a medium-sized city in Colombia, located in the central-eastern part of the country and with an estimated population of 538,523 people (DANE, 2020). The geographic area lies between latitudes 4° 8' 46.17" N and 73° 38' 12.22" W, and latitude 4° 4' 30.83" N and 73° 35' 7.68" W, covering a distance of 11.4 kilometers (Figure 1). This area has an average annual temperature of 27.0 °C, receives approximately 4,172.3

mm of rain per year, and is located at an altitude of 467 meters above sea level. The greatest amount of rain is concentrated between May and October, while January is the driest month (IDEAM, 2020).

**Figure 1.** *Study area and geographic location of the sampling.*



Source: Own elaboration

During September 2024, road dust samples were collected at eight bus stops in Villavicencio. A brush and a tray were used to collect accumulated dust from areas of approximately 1 square meter at each station. Five subsamples were collected at each station along a 100-meter stretch. The sampling sites did not experience precipitation during the prior week or during the sampling period. All samples were stored in polyethylene bags, and the material was homogenized by passing it through a 2.0-mm sieve to remove larger impurities, such as organic material, stones, wires, plastic fragments, wooden chips, plant debris, bricks, and pebbles. Subsequently, all subsamples from each station were combined into a single sample. Sampling points were georeferenced using the Global Positioning System (GPS).

### *2.2. Chemical Analysis*

A conductivity meter was used to measure the electrical conductivity (EC) of 1:5 dust/water extracts and a potentiometer to measure pH values of 1:2.5 dust/water extracts. Organic matter content (OM) (Walkley and Black, 1934). The mineralogical composition of the sample was determined by X-ray diffraction (XRD) using a diffractometer in the two-theta/theta coupled configuration with Cu Kα radiation (λ = 1.54060 Å). The analysis was performed over a 2° to 70° range, measuring the intensity of the diffraction peaks. The concentration of heavy metals (Pb, Cu, Zn, and Cd) in dust samples was determined by microwave-assisted acid digestion followed by analysis using Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES, Perkin Elmer). A combination of strong acids was used to ensure complete dissolution of the solid matrix. Analyses were performed within a detection range of 0.002 to 200 mg $kg^{-1}$, depending on the metal (Pb: 0.008–50 mg $kg^{-1}$; Cu: 0.002–50 mg $kg^{-1}$; Zn: 0.01–200 mg $kg^{-1}$; Cd: 0.002–50 mg $kg^{-1}$). Quality control and reproducibility of results were ensured by performing replicate and duplicate analyses.

### *2.3. Pollution analysis and potential ecological risk factor*

The pollution analysis was carried out using the Geoaccumulation indexes (Müller, 1982), the pollutant load index (Tomlinson et al., 1980) and the potential ecological risk factor (Håkanson 1980). The equations for the calculation are presented in Table 1.

**Table 1.** *Pollution indices and Potential ecological risk ractor ($E_r$)*

| Equation | Description | Classification |
|---|---|---|
| | **Pollution Load Index (PLI)** | |
| $CF_i = \frac{C_i}{C_{oi}}$<br>$PLI = \sqrt[n]{CF_1 \times CF_2 \times \ldots \times CF_n}$ | Where *CFi* is the contamination factor for metal *i*, *Ci* is the concentration of metal in the sample, Coi represents the background value of metal *i*, and PLI reflects the integrated contamination level of multiple metals in a sample. | *Non-pollution* if *PLI* (*CF*) ≤ 1; *slight pollution* if 1 < *PLI* (*CF*) ≤ 2; *moderate pollution* if 2 < *PLI* (*CF*) ≤ 3; and *heavy pollution* if *PLI* (*CF*) > 3. |
| **Geoaccumulation index** | | |
| | | |
| | Where Cs refers to the determined | *Unpolluted if $I_{geo} \leq 0$; unpolluted to moderately* |

| | | |
|---|---|---|
| $Igeo = log_2 \frac{Cs}{1.5 \times Bn}$ | concentrations, and Bn refers to the underlying values. A factor of 1.5 is applied to control the variations of Bn values. | *polluted if 0 < $I_{geo}$ < 1; moderately polluted if 1 < $I_{geo}$ < 2; moderately to highly polluted if 2 < $I_{geo}$ < 3; highly polluted if 3 < $I_{geo}$ < 4; highly to extremely polluted if 4 < $I_{geo}$ < 5; and extremely polluted if $I_{geo} \geq 5$.* |
| **Potential Ecological Risk Factor (Er)** | | |
| | | |
| $E_r^i = (Tr) \times CF_i$ | Where *CFi* is the contamination factor for metal i and Tr is toxic-response factor (TR) (Zn=1, Cu=Pb=5 and Cd=30 | $E_r < 30$ *Slight*; $30 \leq E_r < 60$ *Medium*; $60 \leq E_r < 120$ *Strong*; $120 \leq E_r < 240$ *Very strong*; $E_r \geq 240$ *Extremely strong* |

Source: Own elaboration

*2.4. Statistical Review*

Descriptive statistical parameters, including mean, standard deviation (SD), coefficient of variation (CV%), along with their minimum, and maximum values were calculated. Principal Component Analysis (PCA) was also applied to analyze the road dust variables. PCA was used to reduce dimensionality and identify significant patterns and clusters among the variables, capturing the greatest variance through linear combinations. All statistical analyses were conducted using the SPSS version 25.0 program (IBM SPSS Inc., Chicago, IL, USA).

**Results and discussion**

*3.1. Potentially Toxic Element Contents in road dust bus stop*

Researching anthropogenic contamination by PTEs in road dust is crucial for environmental planning and monitoring in urban settings (Odediran et al., 2021; Chen et al., 2024). This study analyzed the levels of Pb, Cd, Cu, and Zn in dust samples obtained from eight sampling stations (Table 2). The results (shown in table 2) indicated PTEs levels varied between the following ranges (mg kg$^{-}$1): Cd (1.2–0.6), Pb (44.6–15.0), Cu (115.6–17.6) and Zn (519.6–69.8) with averages of 202.3 mg kg$^{-}$1 for Zn, 46.4 mg kg$^{-}$1 for Cu, 27.9 mg kg$^{-}$1 for Pb, and 0.8 mg kg$^{-}$1 for Cd. It was found that the average levels of Pb (27.9 mg kg⁻1), Cd (0.8 mg kg⁻1), Cu (46.4 mg kg⁻1), and Zn (202.3 mg kg⁻1) were higher than the underlying levels (Pb: 11.3 mg $kg^{-1}$; Cd: 0.3 mg $kg^{-1}$; Cu: 9.9 mg $kg^{-1}$; Zn: 28.2 mg $kg^{-1}$), suggesting that human activity may have had an effect. The dust showed neutral pH (mean = 7.6), a considerable organic matter content (mean = 2.78%), and an average electrical conductivity of 0.20 dS/cm. The data showed considerable variation, with coefficients of variation of 76.0% for Zn, 86.1% for Cu, 39.4% for Pb, and 23.8% for Cd. This demonstrates that not all contaminants are distributed in the same way.

**Table 2.** *Results and descriptive statistics of heavy metals, organic matter, electrical conductivity, and pH in road dust from bus stops in Villavicencio, Colombia*

| Bus station | Pb | Cd | Cu | Zn | OM | EC | pH |
|---|---|---|---|---|---|---|---|
| | mg $kg^{-1}$ | | | | % | dS/cm | |
| | | | | | | | |
| Mean | 27.9 | 0.8 | 46.4 | 202.3 | 2.78 | 0.20 | 7.6 |
| SD | 11.0 | 0.2 | 40.0 | 153.8 | 1.0 | 0.08 | 0.3 |
| CV% | 39.4 | 23.8 | 86.1 | 76.0 | 34.6 | 38.90 | 4.2 |
| Máx | 44.6 | 1.2 | 115.6 | 519.6 | 4.8 | 3.9 | 7.9 |
| Mín | 15.0 | 0.6 | 17.6 | 69.8 | 1.9 | 0.15 | 7.0 |
| Reference * | 11.3 | 0.3 | 9.9 | 28.2 | | | |

*Reference values according to Trujillo-González et al. (2022).

Source: Own elaboration

Road dust characterization and monitoring are crucial for assessing environmental quality and potential health risks, especially in urban areas. Road dust carries potentially toxic elements (PTEs) and other contaminants, which can accumulate and pose risks to both ecosystems and human health. Khan and Strand (Khan and Strand, 2018) highlight the health problems posed by road dust, stressing the need for comprehensive analyses of its composition and associated hazards. This section analyzes four essential components present in road dust and their ecological importance.

*Lead (Pb)*

Lead is recognized as a carcinogen derived from mining, refining, and manufacturing. However, it has had a more significant impact on the advancement of contemporary society (Ara and Usmani, 2015). The accumulation of lead in the environment is influenced mainly by vehicle emissions (Root, 2000; Milenkovic et al., 2015). Despite its restricted mobility, lead is extremely dangerous (Poggio et al., 2009). Lead concentrations in these samples ranged from 15.0 mg $kg^{-1}$ to 44.6 mg $kg^{-1}$, The Pb concentrations observed in this study are consistent with previous findings in the region. Trujillo-

González et al. (2019) reported 20.7 mg kg⁻¹ of Pb in road dust along the Villavicencio highway, while Trujillo-González et al. 2025, documented 20.9 mg kg⁻¹ in Puerto López and 16.7 mg kg⁻¹ in Puerto Gaitán, two municipalities near the study area. Approximately the same amount as the global average of lead in clean soils, which was 44.0 mg kg⁻¹ (Kabata-Pendias and Pendias, 2001).

*Cadmium (Cd)*

Exposure to cadmium is associated with kidney disease, lung carcinoma, and osteoporosis. Industries such as paints, pigments, and electroplating use it extensively (Volensky, 1990). Cd, is highly mobile, it accumulates in the human body with prolonged exposure, resulting in chronic health problems. The levels found (0.6–1.2 mg kg⁻¹) are higher than those previously reported in the same city, where values reached 0.04 mg kg⁻¹ (Trujillo-González et al., 2019).

*Copper (Cu)*

Copper is used in fungicides, livestock manure, and atmospheric sedimentation due to its relatively low human toxicity (Poggio et al., 2009). Previous studies have reported an average copper concentration of 47.7 mg kg⁻¹ in road dust (Trujillo-González et al., 2019), while Cu levels in road dust from Villavicencio range between 17.6 and 115.6 mg kg⁻¹. More recent data from nearby municipalities indicate lower Cu concentrations, with 16.3 mg kg⁻¹ in Puerto López and 11.7 mg kg⁻¹ in Puerto Gaitán (Trujillo-González et al., 2025). It is also higher than the global average for pure soils, which is 20–30 mg kg⁻¹ (Alloway, 1995; Kabata-Pendias and Pendias, 2001).

*Zinc (Zn)*

At high concentrations, this critical mineral can exhibit neurotoxicity, which can affect cognitive function and homeostasis (Jiries, 2001). Anthropogenic sources of zinc include agrochemicals, brake pads, and abrasion from vehicles (Ward, 1990; Alengebawy et al., 2021). The Zn concentrations found in this study (42.15 to 81.30 mg kg⁻¹) concide with previous findings in the region, where Villavicencio presented an average Zn content of 118.1 mg kg⁻¹ (Trujillo-González et al., 2019). In contrast, recent studies indicate decreasing Zn levels in nearby municipalities, with 83.9 mg kg⁻¹ in Puerto López and 59.8 mg kg⁻¹ in Puerto Gaitán (Trujillo-González, 2025).

### *3.2. Principal Component Analysis*

The principal component analysis (PCA) determined the main factors influencing road dust contamination in the study area (Table 3). The first principal component (PC1), which explains 45.7% of the total variability, is strongly correlated with Pb, Cu, Zn, and pH, implying that these elements are important indicators of heavy metal contamination, likely caused by vehicular traffic and urban infrastructure wear (Trujillo-González et al., 2019; Nawrot et al., 2020). In contrast, organic matter (OM) has a negative charge in this component, indicating an inverse relationship with metal accumulation. The second principal component (PC2), which accounts for 21.4% of the variance, is dominated by Cd and Zn, indicating an additional source of contamination, possibly due to tire abrasion, brake wear, and industrial waste.

**Table 3.** *Principal component analysis (PCA) on road dust samples*

| Variable | PC1 | PC2 | PC3 |
|---|---|---|---|
| Pb | 1.0 | 0.0 | -0.38 |
| Cd | 0.0 | 1.0 | -0.23 |
| Cu | 1.0 | 0.0 | 0.07 |
| Zn | 1.0 | 1.0 | 0.41 |
| OM | -1.0 | 0.0 | -0.20 |
| EC | 0.0 | 0.0 | 0.83 |
| pH | 1.0 | 0.0 | 0.19 |
| Total | 3.2 | 1.5 | 1.1 |
| % Variance | 45.7 | 21.4 | 16.2 |
| Cumulative Variance | 45.7 | 67.1 | 83.3 |

Source: Own elaboration

The third principal component (PC3), which explains 16.2% of the variance, is significantly correlated with electrical conductivity (EC), suggesting that dissolved salts and soluble metals affect the chemical composition of the dust, possibly due to atmospheric deposition or leaching from urban materials (Sager, 2020). The cumulative variance of the three initial components (83.3%) indicates that these variables represent the predominant source of data variability, highlighting the collective influence of vehicular, industrial, and environmental factors on road dust contamination.

### *3.3. Pollution Levels and Ecological Risk factor Assessment*

Table 4 presents the results of the indexes used to assess the environmental quality of bus stations in Villavicencio, Colombia. The use of indexes such as the Geoaccumulation Index (Igeo), the Contamination Factor (CF), the Pollution Load Index (PLI), and the Potential Ecological Risk Factor (Er) could help in assessing contamination levels concerning PTEs (Haleem et al., 2022; Nasir et al., 2023). These indicators provide a solid basis for assessing potential environmental and human health impacts, measuring contamination levels, and identifying sources (Heidari, 2021). The CF assesses contamination levels in relation to regional reference concentrations, while the Igeo assesses PTEs accumulation based on reference values. The Ecological risk (Er) assesses the ecological hazard posed by PTEs by incorporating their toxicity coefficients (Najmeddin, 2018), while the PLI offers a comprehensive assessment of contamination levels at many sampling locations (Salazar-Rojas et al., 2023).

**Table 4.** *Contamination and ecological risk factors in road dust at bus stops.*

| Bus Stop | Geoaccumulation Index | | | | Contamination Factor | | | | PLI | Potential Ecological Risk Factor | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Pb | Cd | Cu | Zn | Pb | Cd | Cu | Zn | | Pb | Cd | Cu | Zn |
| | | | | | | | | | | | | | |
| Mean | 0.6 | 0.9 | 1.2 | 2.0 | 2.5 | 2.8 | 4.7 | 7.2 | 3.6 | 12.4 | 84.1 | 23.4 | 7.2 |
| SD | 0.6 | 0.4 | 1.2 | 1.0 | 1.0 | 0.7 | 4.0 | 5.5 | 1.4 | 4.9 | 20.1 | 20.2 | 5.5 |
| CV% | 96.8 | 41.9 | 102.2 | 48.9 | 39.5 | 23.9 | 86.1 | 76.0 | 38.8 | 39.5 | 23.9 | 86.1 | 76.0 |
| Min | -0.2 | 0.3 | 0.2 | 0.7 | 1.3 | 1.9 | 1.8 | 2.5 | 2.1 | 6.7 | 56.0 | 8.9 | 2.5 |
| Max | 1.4 | 1.4 | 3.0 | 3.6 | 4.0 | 3.8 | 11.7 | 18.4 | 5.8 | 19.7 | 115.0 | 58.4 | 18.4 |

Source: Own elaboration

The assessment of pollution and ecological risk indicators reveals a fairly wide range of pollution levels among university bus stations in Villavicencio, Colombia (Figure 2). With maximum values of 3.0 for Cu (Bs 3) and 3.6 for Zn (Bs 4), the Igeo shows Cu and Zn have the highest levels of pollution. These findings imply that human activities affect the environmental quality of that area most likely through vehicle emissions, brake wear, and tire abrasion (Baensch-Baltruschat et al., 2020; Kormoker et al., 2021). Pb and Cd, on the other hand, show less accumulation. Their Igeo values fall between -0.2 and 1.4, therefore indicating either minimum to moderate pollution levels. The CF supports these findings. Copper and Zinc had maximum CF values of 11.7 (Bs 3) and 18.4 (Bs 4), thereby indicating highly contaminated areas in these locations. Although Pb and Cd show only moderate levels of contamination, their presence adds to the overall contamination burden in urban dust.

The PLI averages 3.6 ranging from 2.1 to 5.8. This indicates that many bus stops, especially at Bs 1 and Bs 4 where metal accumulation is typically higher, exhibit moderate to high levels of pollution. Cd was the main contributor at each sampling site, according to the ecological risk assessment. It had a peak value of 115 at site Bs5, which is near the very strong risk threshold, and a mean Er value of 84.1, which indicates a strong risk. This indicates the need to take extra care because cadmium is extremely toxic and persists in the environment for a long time. With mean Er values of 12.4 and 23.4, respectively, Pb and Cu were of moderate concern. However, higher levels in some hotspots, such as Bs2 for Pb and Bs3 for Cu, indicate localized emissions, most likely from fuel combustion and brake wear. Diffuse sources were identified because Zn, which had the lowest toxic response factor, showed low risk levels (average Er = 7.2) and varied considerably between areas (CV = 76%). Based on these findings, cadmium poses the greatest environmental risk in urban dust, while lead and copper should be closely monitored to reduce the likelihood of further problems.

### *3.4. Mineralogical composition of Road Dust*

The mineralogical composition of road dust is a heterogeneous amalgamation of natural and artificial elements, with variations influenced by geographical location and adjacent activities. The mineralogical analysis, performed using X-ray diffraction (Table 5, Figure 3 and 4), indicated that quartz ($SiO_2$) was the main mineral, representing approximately 90% of the total composition. Other minerals were contained in smaller amounts including muscovite (4.65%) [($K_{0.93}Na_{0.07}Al_{1.83}Fe_{0.17}Mg_{0.03}(Al_{0.82}Si_{3.18})$]), albite (3.18%) [($(Na_{0.98}Ca_{0.02})(Al_{1.02}Si_{2.98}O_8)$]), and chlorite (1.24%) [(($Al_{2.96}Fe_{6.74}Mg_{2.38})(Si_{5.24}Al_{2.76})$ In addition, traces of kaolinite [($Al_2(Si_2O_5(OH)_4)$] and microcline [($(K_{0.95}Na_{0.05})(AlSi_3O_8)$)] were identified.

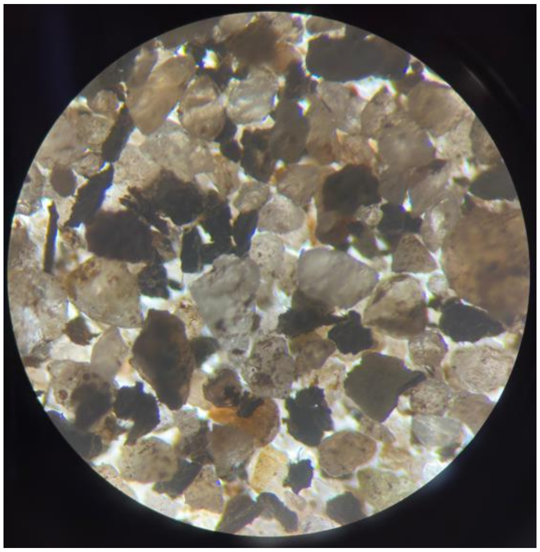


**Figure 2.** *Observation of road dust samples at 2X magnification using a stereoscopic microscope (SteREO Discovery.V8, ZEISS; Carl Zeiss Canada).*

Source: Own elaboration

These results support previous work by Candeias et al. (Candeias et al., 2020), who also found that quartz was the main mineral, especially in the coarse fraction. Other minerals found were muscovite [($KAl_3Si_0O_{10}(OH)_2$)], albite [($NaAlSi_0O_8$)], kaolinite [($Al_2Si_2O_5(OH)_4$)], microcline [($KAlSi_0O_8$)], Fe-enstatite [$(Fe,Mg)_2Si_2O_6$], and graphite [(C)]. As noted by Gunawardana et al. (Gunawardana et al., 2012) the minerals found probably come from weathered rock and clay fractions with low detection thresholds, as well as from artificial sources.

**Table 5**. *Mineralogical analysis obtained from x-ray diffraction of a composite sample of road dust taken from eight bus stop subsamples*

| Mineral Name | Chemical Formula | Quantitative (%) |
|---|---|---|
| Quartz | $SiO_2$ | 89.83% |
| Muscovite-2M1, $Fe^{3+}$ exchange | $K_{0.93}Na_{0.07}Al_{1.83}Fe_{0.17}Mg_{0.03}(Al_{0.82}Si_{3.18}O_{10})(OH)_{1.79}O_{0.21}$ | 4.65% |
| Albite | $(Na_{0.98}Ca_{0.02})(Al_{1.02}Si_{2.98}O_8)$ | 3.18% |
| Chlorite-Iib | $(Al_{2.96}Fe_{6.74}Mg_{2.38})(Si_{5.24}Al_{2.76})O_{20}(OH)$ | 1.24% |
| Kaolinite-1A | $Al_2(Si_2O_5(OH)_4)$ | <1% |
| Microcline | $(K_{0.95}Na_{0.05})(AlSi_3O_8)$ | <1% |

Source: Own elaboration

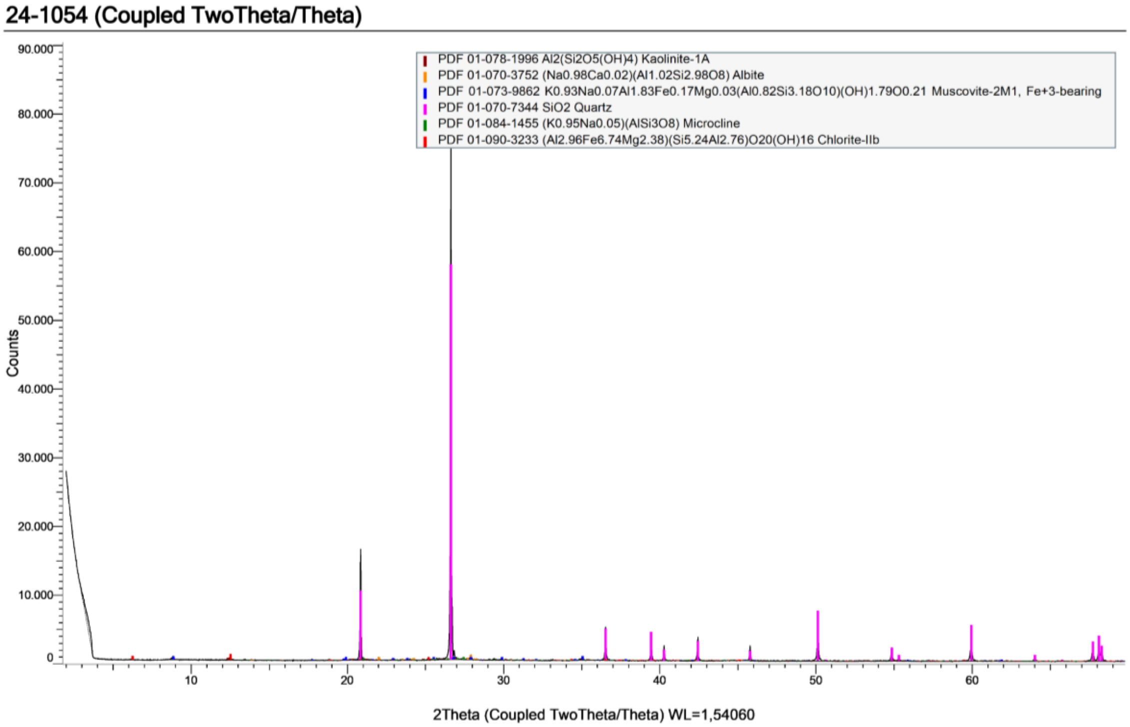


**Figure 4.** *X-ray diffractogram of a composite sample of road dust taken from eight bus stop subsamples*

Source: Own elaboration

The mineralogical analysis of road dust is essential to determine its origin, whether natural (rock weathering, soil resuspension) or anthropogenic (vehicle emissions, industrial operations) (Navarro-Ciurana et al., 2023). According to the data, the components of road dust are modified by both natural processes, such as rock weathering, and human activities, such as infrastructure construction and car emissions. The prevalence of quartz is consistent with prior research on urban dust, indicating its role as a conduit for heavy metals. Understanding the mineral composition of dust is crucial for assessing air quality as certain minerals can contain hazardous compounds or cause respiratory problems. This information also helps to identify contamination sources, facilitates environmental monitoring, and guides urban planning policies aimed at reducing health risks and environmental damage.

## Conclusions

This research provides a comprehensive assessment of PTEs contamination in road dust at the university bus stop in Villavicencio, Colombia. The amounts of Pb (15.0–44.6 mg kg$^{-1}$`), Cd (0.6–1.2 mg kg$^{-1}$), Cu (17.6–115.6 mg kg$^{-1}$), and Zn (69.8–519.6 mg kg$^{-1}$) are much higher than what other studies have found in the area and what are the background levels. These high levels underscore the impact of human activities, especially vehicular emissions, brake degradation, and tire erosion. Igeo classifies the amount of Cu and Zn contamination as moderate to high. Maximum values of 3.0 Cu at Bs 3 and 3.6 Zn at Bs 4 indicate that these areas have significant contamination. The CF corroborates these results, indicating maximum values of 11.7 for Cu (Bs 3) and 18.4 for Zn (Bs 4). The PLI varies from 2.1 to 5.8, with a mean of 3.6, indicating widespread contamination. The most hazardous element is Cd, which has the highest Er value of Bs 5 (115.0). Therefore, it is considered a very heavy contaminant.

In addition to metal contamination, a study of the minerals present in road dust shows that quartz ($SiO_2$) is the predominant mineral, representing approximately 90% of the total. Other minerals found are muscovite (4.65%), albite (3.18%), chlorite (1.24%), and small amounts of kaolinite and microcline. From a public health perspective, these results highlight the importance of systematic monitoring programs and targeted mitigation strategies to reduce human exposure to hazardous metals in cities. Authorities should implement more stringent pollution control measures, including improved road dust management and stricter emission limits, particularly in high-traffic areas such as bus stops. Further research is needed on the bioavailability of these elements, their interaction with mineral phases, and their long-term impact on health and the environment.

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